BLAST TESTING OF EXPEDIENT SHELTERS IN MODEL SCALE

by

Edward D. Esparza
Southwest Research Institute
San Antonio, Texas

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ABSTRACT

A research program was conducted to evaluate the blast resistance of expedient fallout shelters designed for the civilian population in the event of a nuclear attack. As part of this research, model size shelters of six different designs were tested in a shock tunnel at average overpressure levels of 2.8, 4.6, and 8.8 psi. Measurements of the external blast pressures and internal pressure leakage into the model shelters were made. The expedient shelters tested utilize, in general, shallow soil excavation, load-bearing members of timber or doors, and soil-covered roofs. Replica model sizes were selected so that the shock tunnel load durations were long enough to test in the quasi-static load realm. An elevated soil section was used in the tunnel to test 96 response models in 12 experiments. Some of the shelter designs survived at every overpressure level very well, while other test items suffered structural failures in almost every case. This paper presents a brief description of the experiments, including some details of the shelters, of the model fabrication and pressure measurement system, and a summary of the results.

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INTRODUCTION

A number of do-it-yourself shelters have been designed and recommended for providing protection to families or other small groups from deadly radiation and radioactive fallout generated by a nuclear detonation [1,2]. Shelter designs vary to accommodate different local soil conditions and available materials. For example, in areas where below ground shelters are impractical due to a shallow water table or bedrock, the expedient shelter recommended would be above ground. For areas with an abundance of small trees, the structural materials specified are wooden poles of various lengths. For areas where there is a shortage of small trees, household doors are used as the load-bearing members. However, for all designs, a thick earth cover and walls are used as the primary radiation shield.

Some of these shelters had been tested in high explosive nuclear simulation tests [3,4]. Generally, the results of these limited tests yielded qualitative results of a shelter at a particular overpressure range. To better evaluate the level of blast protection expedient shelters provide to occupants, an analytical and experimental program was conducted by Southwest Research Institute (SwRI) [5]. In this program, a literature search was conducted to identify expedient shelter designs. Eight selected designs were then evaluated analytically to determine expected failure mechanisms and to estimate the blast overpressures at which structural failures such as overturning, trench collapse, or roof collapse would be expected to occur. Six different shelter designs were then tested in a shock tunnel in model scale after several physical models were considered. Replica models were used because of the limitations on the available shock tunnel facility. The results from a series of twelve experiments involving 96 structural response models were used to determine the blast protection provided by each of the six types of shelters tested. Complete details of this shelter evaluation program are found in Reference 5. This paper presents brief descriptions of the six expedient shelters tested, an overview of the test program, some details of the experiments and pressure measurement system, examples of pressure traces, and a summary of the results.

DESCRIPTION OF EXPERIMENTS

Shelters

The six expedient shelters selected for testing are depicted in Figures 1-6 and were as follows:

- Door-covered trench shelter
- Above ground door-covered shelter
- Crib-walled shelter
- Ridge pole shelter
- Small pole shelter
- Log-covered trench shelter

The below ground shelters generally utilize an excavation with a soil-covered roof to provide protection from fallout. The earth cover is specified to be a minimum of 2 to 3 feet deep and is supported on a load-bearing roof of timbers or household doors. The excavations are about 4 to 6 feet deep with vertical walls. The above ground shelters have very shallow or no excavation specified in their construction. They use an earth-covered, load bearing roof of timbers or wooden doors about 1.25 to 2 feet deep, and an earth-mound or earth-filled walls about 2 to 4 feet deep.

For the shelters tested, the primary criterion for shelter acceptability was that occupants not be mortally injured. The damage mechanisms that were used to evaluate the level of protection the shelters afforded the occupants were classified as the exposure to overpressure, debris impact/burial, and occupant translation/impact. Because structural failures would create any or all of these occupant damage categories, failure modes for each of the shelters tested in model scale were identified and are listed in Table 1.

Scaling Considerations

A complete model analysis was conducted. Twenty parameters were used to describe the blast loading, ambient conditions, the soil, the shelter structure, and the shelter response. Using the Buckingham Pi Theorem [6], a set of 17 independent dimensionless ratios called pi terms was developed. Model and prototype systems are equivalent when the dimensionless ratios are the same in both. Sometimes this specific requirement cannot be satisfied

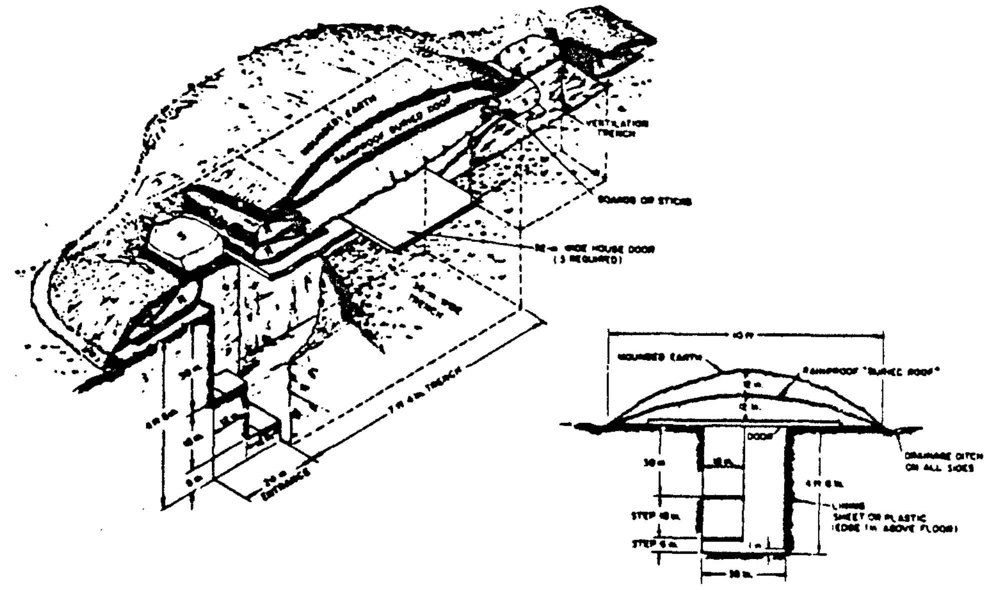


Figure 1. Door-Covered Trench Shelter (References 1 and 2)

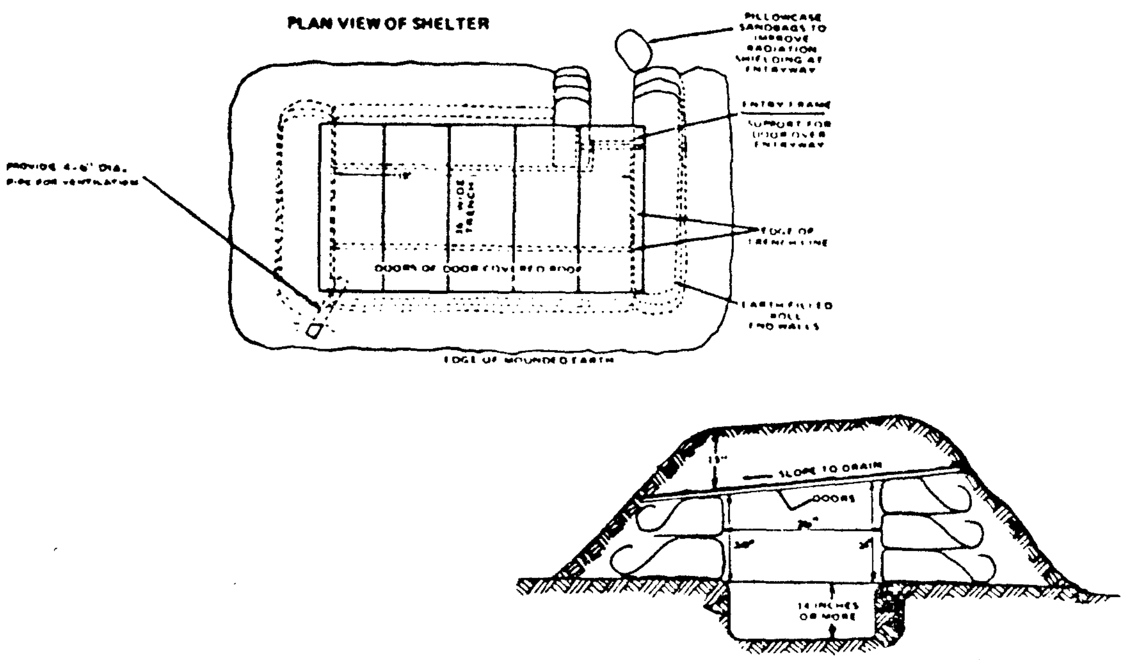


Figure 2. Above Ground Door-Covered Shelter (Reference 1)

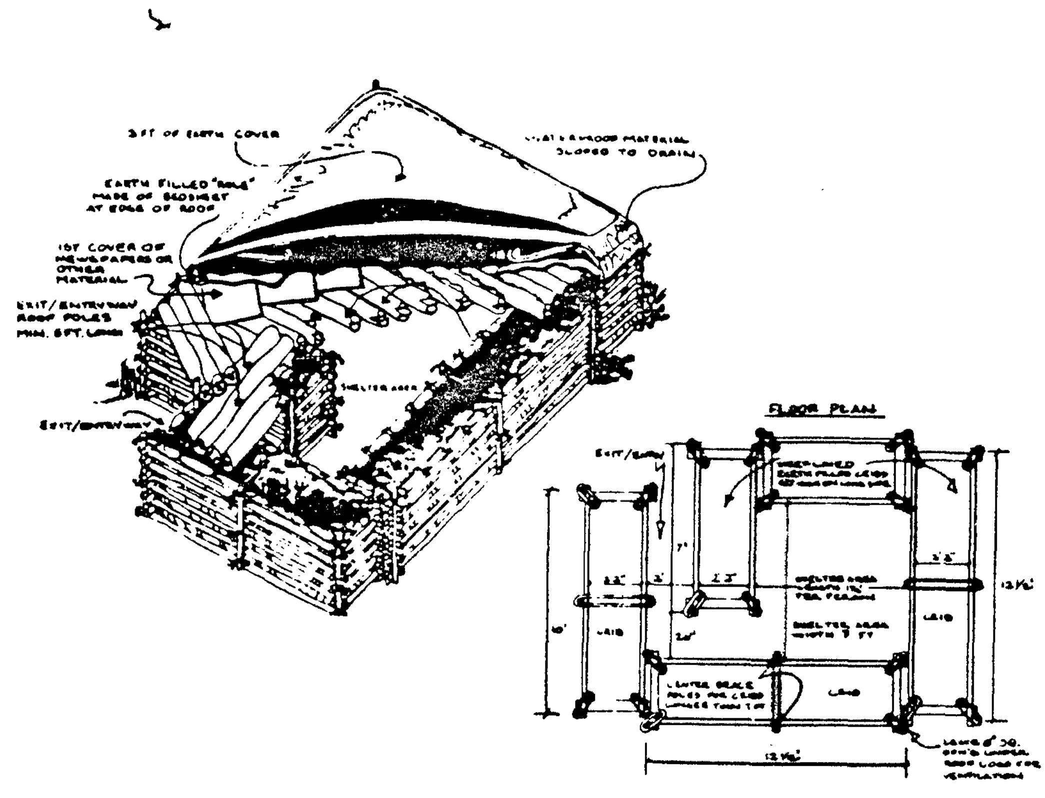


Figure 3. Crib-Walled Shelter (Reference 1)

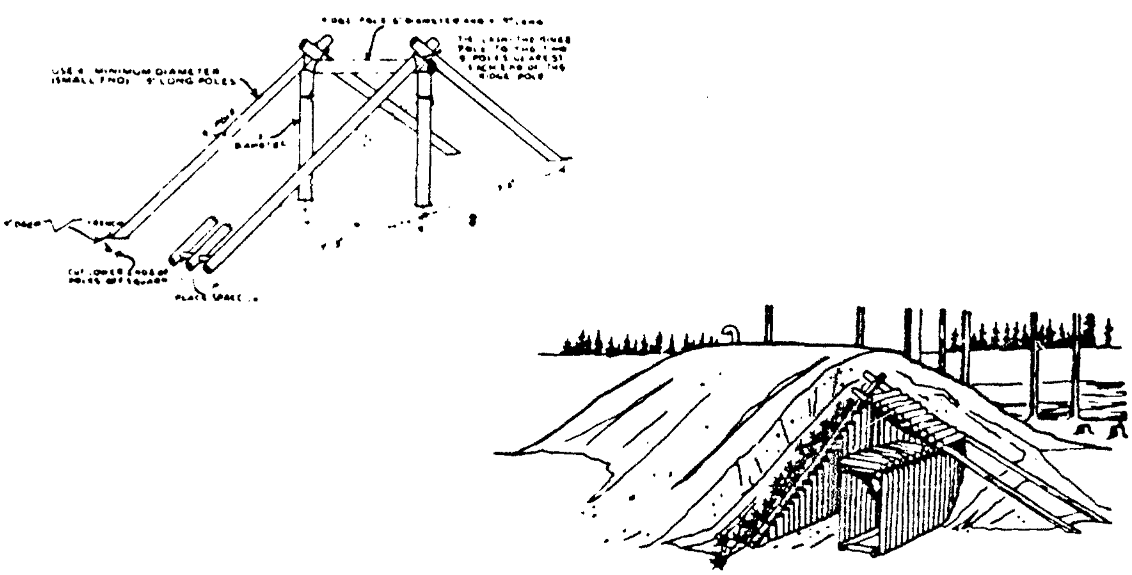


Figure 4. Ridge Pole Shelter (Reference 1)

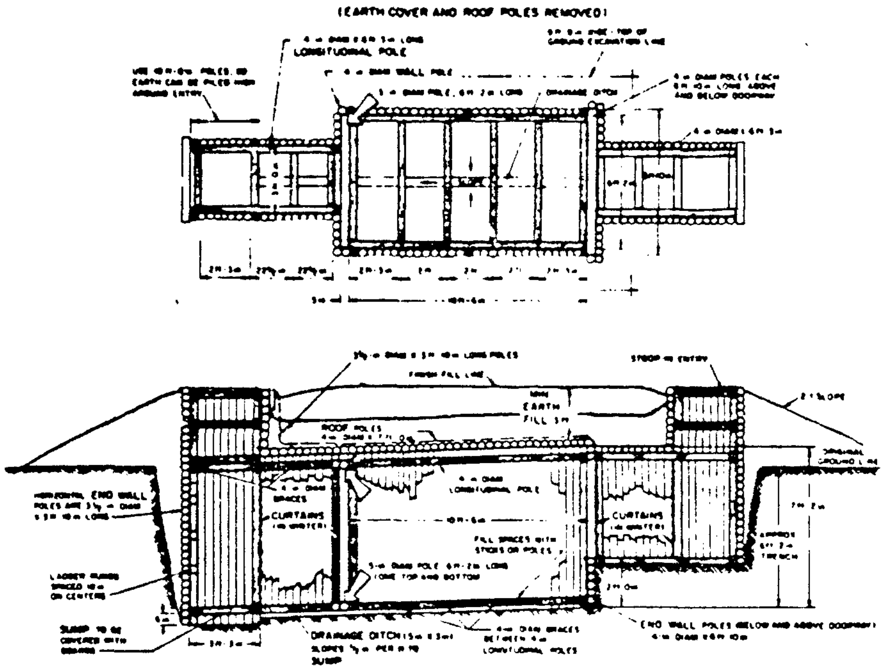


Figure 5. Small Pole Shelter (Reference 2)

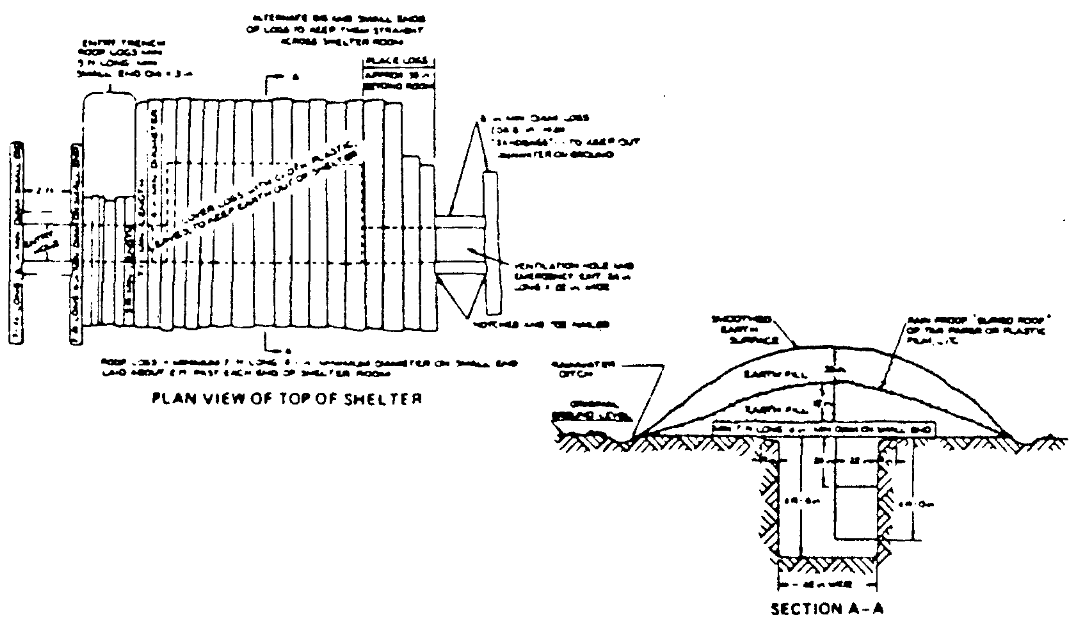


Figure 6. Log-Covered Trench Shelter (Reference 1)

Table 1. Shelter Failure Mode Possibilities

Shelter	Overturn/ Translation	Trench Collapse	Roof Collapse
Door-covered trench		*	*
Above ground door-covered	*		*
Crib-walled	*		*
Ridge Pole	*		*
Small Pole		*	*
Log-covered trench		*	*

because of limitations in the test facility, in the physical properties of the materials, in having a constant gravitational field, in how small the model can be made, and in construction techniques.

Testing of the model shelters was intended to simulate loadings from a 1 megaton (MT) yield weapon at a distance where the side-on overpressure would be greater than 2 psi. A shock tunnel located at Fort Cronkhite, California [7], was provided by the government for testing. The shock tunnel has a maximum overpressure capability of about 8 psi with a positive duration of about 100 ms. Three different modeling approaches were considered: replica, Froude, and dissimilar material. Replica modeling was selected because it was the most practical and least affected by the limitations of the test facility.

In a replica model all components in the model are made of the same materials as in the prototype, and all geometries are similar. Therefore, all lengths and times are scaled by a factor λ ; density, stress, strain, and pressure remain invarient; and accelerations scale as $1/\lambda$. Because the acceleration of gravity cannot be varied in the test facility, gravitational effects were distorted between model and prototype. For the type of response expected from the shelter models, this distortion was considered to be of secondary importance.

Another problem for replica models caused by facility limitations was that the maximum overpressure of 8 psi that can be generated in the Fort Cronkhite tunnel has a 100 ms duration. Assuming that 1/10-scale shelter models were tested, this duration would correspond to 1.0 sec in full scale. A 1 MT nuclear explosion blast wave at the 8 psi level would have a duration of 2.8 sec. Fortunately, calculation of the response time of the various

structural components of the expedient shelters showed that the fundamental period for each full-scale shelter was considerably shorter than the duration of the overpressure load. Thus, the shelters were loaded in the quasi-static realm. Provided the response of the models was also in this domain, the duration of the loading did not have to be scaled rigorously. This was the case since the duration of the tunnel blast wave was about 4 to 45 times longer than the natural period of each model shelter depending on type.

The other two types of modeling considered were eliminated because in one case testing was required to be conducted in a reduced atmospheric pressure with model materials that were weaker by the scale factor, but of the same density, and with loading times that were longer than those required by the replica models. Evacuation of the expansion chamber in the shock tunnel was not possible. In the second case, to obtain longer scaled durations, a different, denser gas is required. This would have also required stronger model materials. However, because the shock tunnel could not be used practically with any gas other than ambient air, this modeling technique was eliminated.

Test Facility and Model Fabrication

The Fort Chronkhite shock tunnel located near San Francisco was specified and provided by the government for the model shelter evaluation program. The tunnel consists of a 63-foot long cylindrical compression chamber about 7 feet in diameter in which strands of Primacord® are used to generate the blast loads. The blast wave expands into a rectangular, 8.5 X 12 feet, cross-sectional expansion chamber about 100 feet long. A major consideration in test planning was the arrangement of model-scale test structures within the expansion chamber of the Fort Cronkhite facility, and the effects of this arrangement on blast loads on the structures. Some of the expedient shelters involve some sort of trenching, so that much of the shelter is below grade. To simulate such shelters within the test facility, a soil-filled test section was installed inside the shock tunnel to allow preparation or insertion of model-scale shelters underground. Nominal length and height dimensions of the test section are given in Figure 7. Laterally, the test section spanned the entire width of the tunnel (12 feet). To allow smooth shock wave loading approaching the models, a ramp was installed upstream at the front of the test bed. Downstream of the models, the test bed was continued to prevent

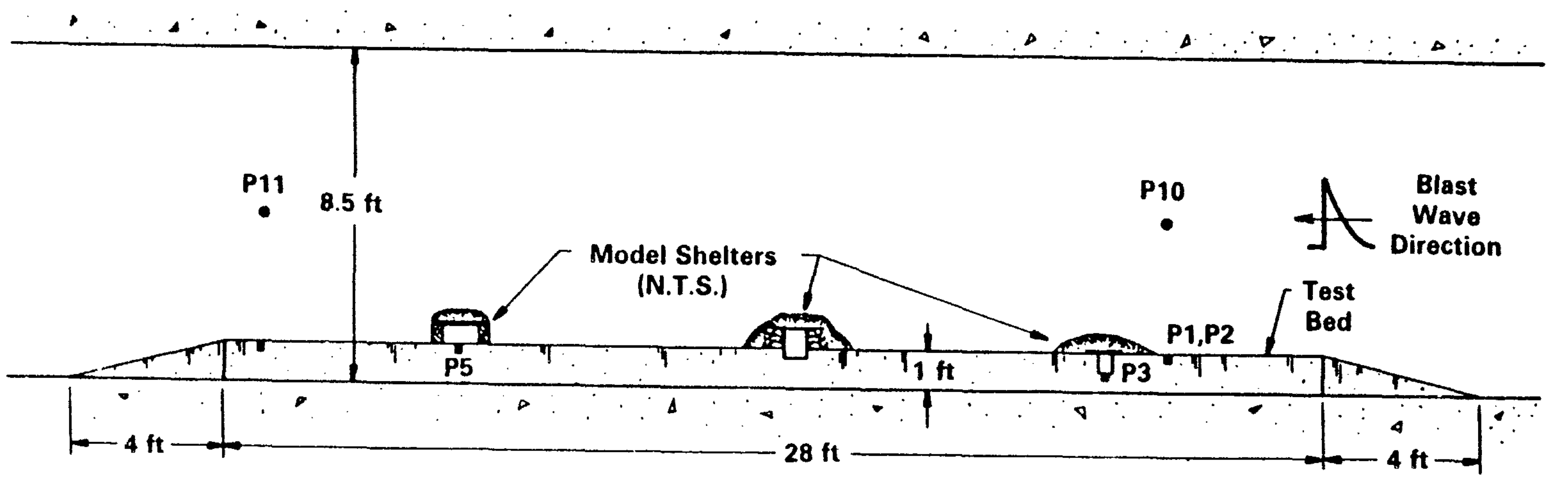


Figure 7. Elevation View of Soil Test Section in Tunnel

premature expansion of the incident shock wave and a down ramp was also installed. By providing a 1-foot high elevated floor over a 28-foot length of the tunnel floor, several models could be tested at one time.

An estimate of the flow over the models was made to approximate the worst-case shock loading that would occur. The blockage factor due to the elevated floor was small, and the elevated floor provided enough depth for sublevel structures to be incorporated into the earth. With a 1-foot elevated surface, side-on shock pressures were expected to be increased by less than 10 percent over the pressure that would be obtained were the tunnel to be used in the usual fashion.

By considering the interference drag that results between the models after the passage of the shock front, the spacing between models was determined. The spacing between models in tandem was that spacing necessary to eliminate interference drag. A similar approach was used to evaluate the spacing needed to eliminate interference drag in the tunnel axial direction. This method of determining spacing requirements followed procedures used to space obstacles in a conventional wind tunnel. By this technique, it was determined that ten, two-abreast models could be tested during one test run using the 28-foot long elevated test surface.

Axial spacing, based on this procedure, required that the test models be at least four to six feet apart on centers, with the first pair of models being four feet behind the transition from the 14-degree ramp up to the test surface. The last set of models was to be three feet forward on centers from a 14-degree ramp down to the shock tunnel floor. Recommended lateral spacing was based on having models with the lowest profile located toward the front edge of the elevated test bed. The last set of two models could be any of the models in pairs or in duplicate. The shelters were about three to four feet from a side wall to the edge of the model. Shock diffraction interference with these arrangements was expected not to be significantly different or altered from that found on an isolated model.

In determining the loading realm and selecting model sizes, response times were estimated for the shelters. Fundamental vibration frequencies were calculated for the main strength structural members. Wooden dowels of comparable strength were chosen to represent logs in the pole shelters. Main structural members in the shelters using wooden poles were generally specified

to be four inches in diameter. Use of 3/8-inch wooden dowels to model these poles resulted in a scale factor λ of 1/10.7 for these shelters. Several types and sizes of plywood were tested along with solid door sections to select modeling materials and sizes. Utile plywood, 3/16-inch thick, was selected to model doors serving as structural members. Using 3/16-inch plywood to model the nominal 1-3/8 inch thick doors resulted in a scale factor of 1/7.33.

Six different fallout shelters were tested in this project to determine their structural blast resistance. As indicated in the introduction, two other shelters were originally identified for evaluation, but were eliminated from testing. The eight shelters were numbered for identification, and the six that were tested are listed in Table 2 along with the scale factor used to size their components. The models of the six expedient shelters were prefabricated as much as possible at SwRI prior to departure to the Fort Cronkhite shock tunnel. In some cases, such as shelter 7, it was possible to assemble the complete wooden structure at SwRI. In other cases wooden subassemblies were put together before departure and later assembled at the test site. Finally, for some shelters (for example, shelter 2), only the model components for the logs and doors could be prepared at SwRI, and the complete assembly was effected at the test site. For those shelters which used soil trenches, wooden molds were fabricated at SwRI and used to form the trenches in the soil test bed.

Table 2. Model Expedient Fallout Shelters Tested

Shelter No.	Shelter Name	Scale Factor
2	Door-covered trench	1 : 7.33
3	Above ground door-covered	1 : 7.33
5	Crib-walled	1 : 10.7
6	Ridge pole	1 : 10.7
7	Small pole	1 : 10.7
8	Log-covered trench	1 : 10.7

The door-covered trench shelter is an example of one of the below ground designs for which a mold was made and used to form the trench. The procedure for making the trench was begun by digging a slightly oversized hole in the test bed, filling, and tamping the soil at the bottom of the hole to obtain the required depth for the trench. The mold was then placed in the hole and backfilled, and hand-tamped in layers with a two-by-four board. The soil used to backfill and to cover the shelters was sifted using a sieve made from 1/4-inch wire mesh. Water was then added to obtain a moisture content of about 10 percent, a level which provided the best soil workability in making the trenches with the mold. Figure 8 shows the trench for a No. 2 shelter. After all the trenches for these shelters were completed, their assembly followed strictly the plan illustrated in Reference 1. The earth-filled rolls were made using Saran Wrap® for the plastic material specified in the shelter plan [1]. The same type of wrap was used to rainproof the roof soil cover. Figure 9 provides an example of a completed No. 2 shelter just prior to testing. Shelters 3 and 8 were two other shelters whose assembly was done at the test site using a wooden mold to form a trench.

Shelter 5, the crib-walled above ground shelter, is an example of a shelter that was to a great extent, prefabricated in subassemblies at SwRI. The five required cribs for each of the five models made were all completed prior to arriving at the test site. In addition, the roof poles were precut in sets for each model shelter. Note that a significantly larger number of poles were required to make the roof than is specified in the instructions for the full-scale shelter in Reference 1. The cribs were assembled and filled with soil as specified in the shelter plan using plastic wrap to line each crib. Figure 10 showsa model of shelter 5 during assembly. The earch cover was then placed on the roof as specified. Figure 11 shows a completed model sheltefr 5 ready for testing. Shelter 6 was another shelter that was partially assembled at SwRI before completing at the test site.

Shelter 7, the small-pole shelter, was the only shelter evaluated in this program that is detailed only in Reference 2. Five models of this shelter were completely fabricated and assembled prior to departure from SwRI to the Fort Cronkhite shock tunnel. Each of these model shelters was installed in the test bed by first digging a slightly oversized hole of the specified depth, placing the assembled shelter in the hole, and then backfilling and

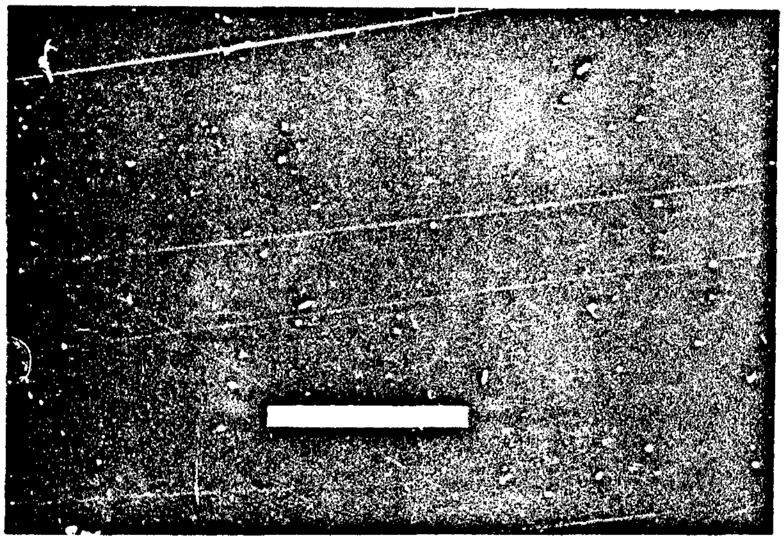


Figure 8. Soil Trench for Door-Covered Trench Shelter

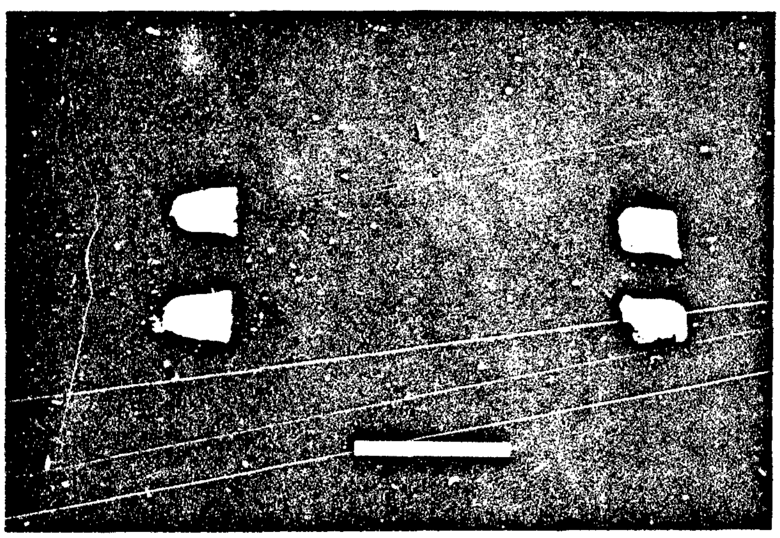


Figure 9. Completed Model of Door-Covered Trench Shelter

data stored on the diskettes were then read into a DEC 11/70 minicomputer, and engineering plots were prepared using a Printronix 300 printer/plotter.

Test Matrix and Procedure

A total of 96 individual shelter response models were tested in the twelve experiments conducted at the shock tunnel. Each test consisted of setting up eight of the response models plus the two rigid models in the test section of the tunnel. To stay within the blast overpressure capabilities of the test facility, the tests were run at three nominal overpressures: 2, 4, and 8 psi. The number of shelters tested at each of these overpressures is listed in Table 3 together with the number of tests. The first five experiments were all at the lowest overpressure. Those shelter designs that survived easily were not tested as often. Also taken into consideration was the complexity of the erection procedure as well as the number of models that had been preassembled or for which parts had been fabricated. In general, those types of shelters that did not survive or appeared close to failure were tested in greater numbers. Three of the highest pressure tests were conducted next. For these tests, about the same number of samples were tested from each type of shelter.

The next three tests used the intermediate overpressure levels, and generally tested a similar number of samples from each type except the one type that had survived the best at the highest pressure level without a

Table 3. Response Models Tested

Shelter No	Nominal Overpressure (psi) 2	4	8	Total
2	7	5	5	17
3	16	7	5	28
5	2	4	5	11
6	5	4	6	15
7	2	0	5	7
8	8	4	6	18
No. of tests	5	3	4	12

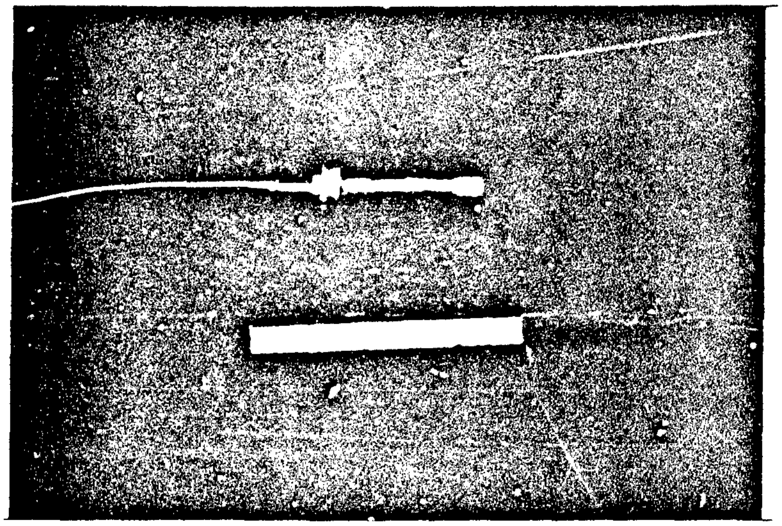


Figure 14. Pressure Transducer Canister

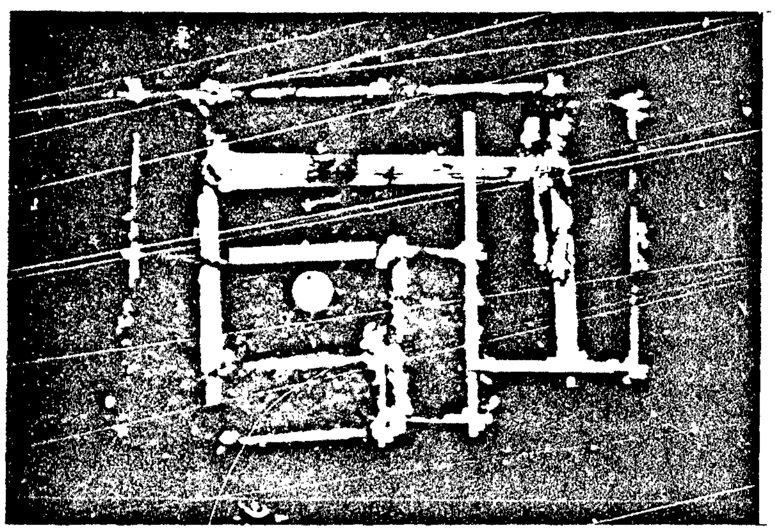


Figure 15. Typical Transducer Installation in Shelters

tamping the soil all around the shelter to obtain the results shown in Figure 12. Soil was then piled over the roof poles as specified in the shelter building instructions using plastic wrap for the rainproofing material in between the earth cover. A completed model shelter 7 is shown in Figure 13.

In addition to the response models of the six shelters listed in Table 2, two rigid models were used on each of the 12 blast experiments conducted in the shock tunnel. The two rigid models represented geometrically shelters 5 and 8. These rigid models were used to measure internal blast pressure leakage into these expedient shelters on every test. The rigid model of the crib-walled shelter 5 was fabricated from solid sections of wood with provisions for mounting pressure transducers on the roof and walls. The rigid model of the log-covered trench shelter 8 was constructed from thin aluminum plate.

Pressure Measurements System

Pressures were sensed and recorded on each test. In all twelve tests, five transducers were mounted to sense the blast overpressure on the test bed and on one wall of the tunnel as shown in Figure 7. In addition, up to seven other transducers were mounted in each test on the rigid and response models of the expedient shelters to sense internal blast pressures. Two types of transducers were used to sense these pressures, piezoresistive and piezoelectric. The piezoresistive pressure transducers used to make the majority of the measurements were Kulite Model HEM-375 with a pressure range of 0-25 psig. This sealed miniature transducer is an all metal, electron beam welded assembly featuring a metal diaphragm as a force collector with piezoresistive strain gages bonded inorganically. These transducers feature a high resonant frequency of approximately 50 kHz, good linearity, and static pressure response. Excitation voltage, bridge balance, and amplification for these pressure transducers were provided by Vishay Model 2310 signal conditioning amplifiers with the frequency response set at dc to 25 kHz (-5%).

The piezoelectric transducers used for the rest of the test measurements were all manufactured by PCB Piezotronics. Two Model 102A02 transducers were mounted on the tunnel wall, one near the front of the test bed and the other near the back. Their output was recorded by SwRI together with the output of the Model 102A05's and 102A15's installed on the test bed and in the model shelters. All three types of PCB transducers utilize an acceleration-

compensated, quartz sensing element coupled to a miniature source follower within the body of the transducer. The source follower converts the high impedance charge output into a low impedance, voltage output signal. The sensors have a rise-time capability of 1 microsecond. Each piezoelectric transducer was connected to a PCB Model 494A06 signal conditioner and amplifier. The amplifier has a specified frequency of 0.08 to 180,000 Hz (-3db) and a coupling time constant of 2 seconds.

Both types of pressure transducers were installed in protective steel canisters which simplified handling and installation in the soil test bed. Figure 14 shows a completely assembled transducer canister ready for burial. For those transducers used to sense the surface overpressure on the test bed, the steel canister was buried so that the transducer was flush with the ground surface. In a similar manner, the transducer canisters were mounted within the model shelters to sense the internal pressures. Figure 15 shows a typical installation in a crib-walled shelter.

The amplified signals from both the piezoresistive and piezoelectric pressure transducers were recorded at the test site on magnetic tape with an Ampex Model 2230 tape recorder with Wideband II, FM electronics. At a record speed of 30 inches/second, the specified data bandwidth capability was 0-100 kHz (+1, -2db). The pressure data were played back at the test site after each experiment using a Biomation Model 1015 four-channel transient recorder. The data traces were recorded on Polaroid film for quick-look analysis using a Tektronix Model 602 display unit. Upon return to SwRI from the Fort Cronkhite facility, the test data were played back and digitized using the system shown in Figure 16. Up to four channels of data were played back at one time through the analog filters into a Biomation Model 1015 four-channel transient recorder. This recorder digitizes the incoming analog signals at sample intervals of 0.01 milliseconds or greater. Since this unit has four separate analog-to-digital (A/D) converters, the samples for each of the four data channels are time correlated. Once the test data were properly formatted in digital form, a DEC 11/23 computer extracted the data from the transient recorder memory through the computer Automated Measurement and Control (CAMAC) data buss and stored them on a 8-inch flexible diskette. A graphics terminal was used to display each data trace for verification. The

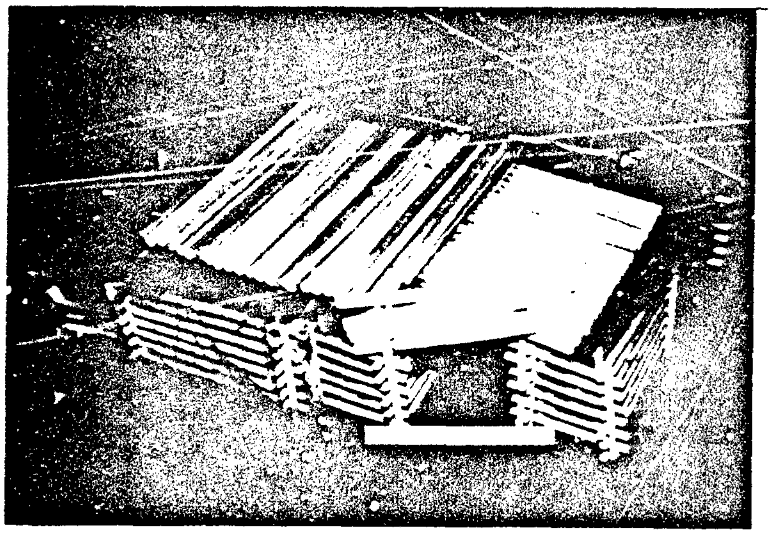


Figure 10. Assembling of Crib-Walled Shelter

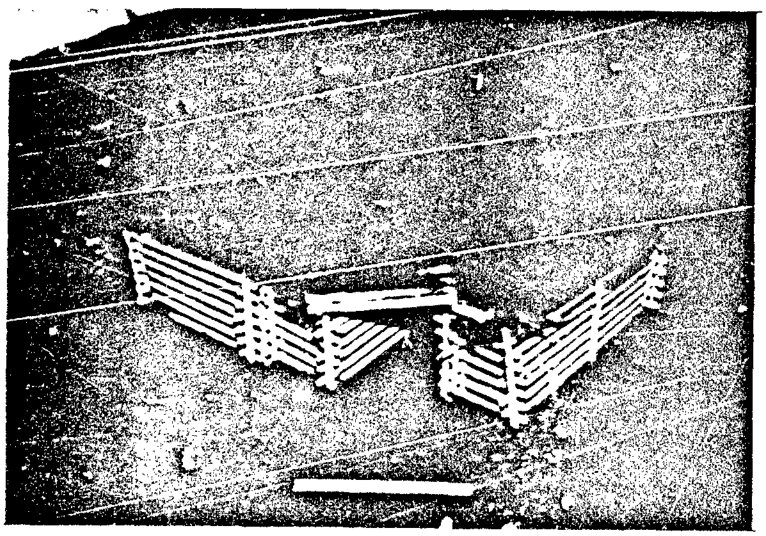


Figure 11. Completed Model of Crib-Walled Shelter

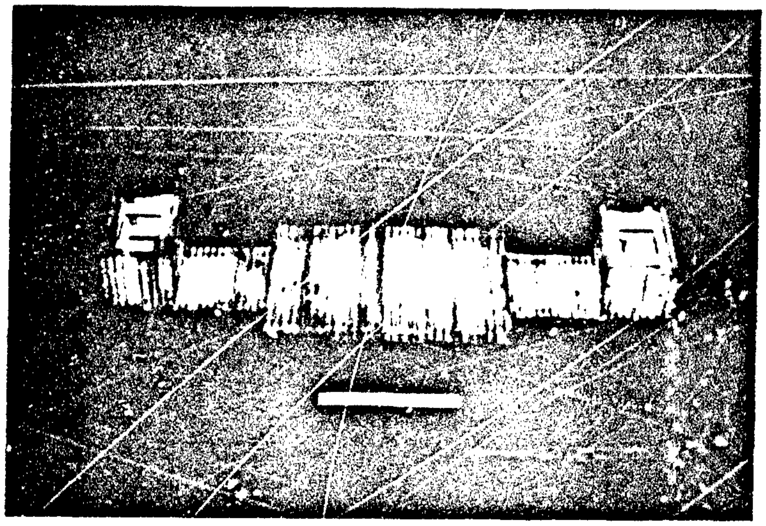


Figure 12. Burial of Small Pole Shelter Assembly

Figure 13. Completed Model of Small Pole Shelter

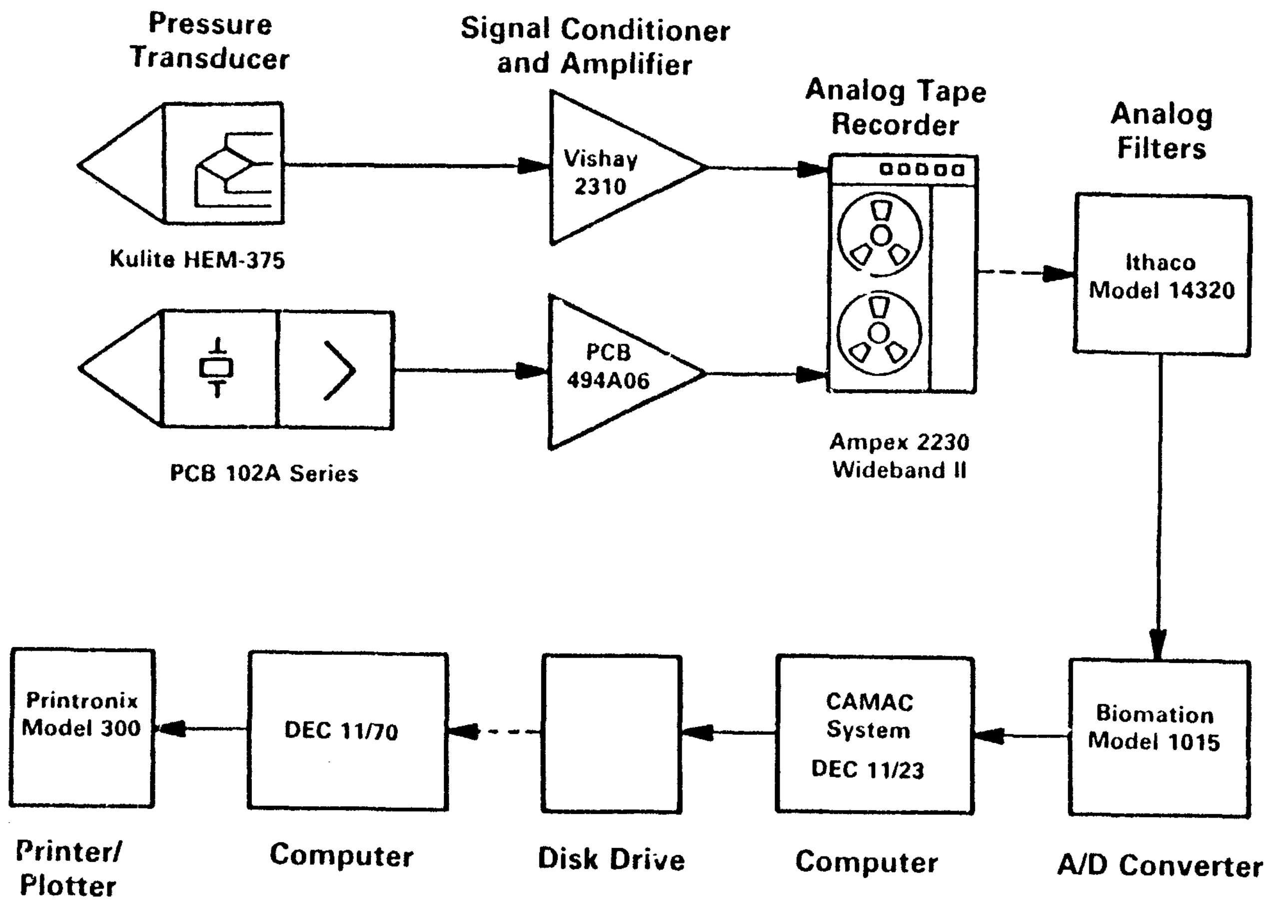


Figure 16. Data Recording and Processing System

failure. Included in this series of tests were two shelter models that were modified slightly to determine if their performance could be improved. The last test was at the highest pressure level and it included four of the shelters in slightly modified forms. A total of only six shelter models were tested in a slightly modified condition in the entire test program.

All 12 experiments in this program followed a similar test procedure regardless of which model shelters were being tested and which pressure level was used. As indicated previously, eight response shelters were installed in the test bed in each experiment along with two rigid models. The normal test sequence was begun by measuring carefully and marking on the soil test bed the location of each model shelter. Then, each model shelter was assembled or installed in place following the instructions provided in Reference 1 for five types of shelters and in Reference 2 for one type of shelter.

While all the model shelters were being installed, the pressure measurement system was set up and checked for proper end-to-end operation. Amplifier gain and tape recorder voltage levels were set to accommodate the peak pressure expected. After the model shelters were completed and the measurement system configured properly, the exit from the shock tunnel was closed and Primacord® explosive placed in the compression tube. The back door to the compression tube was then closed, and the area around the shock tunnel was secured. After a short countdown sequence, the explosive array was detonated, and the pressure data were recorded.

The tunnel exits and back door were then opened to allow natural ventilation of the explosion gases before test personnel would return to the test section of the tunnel to record the condition of the test shelters. In the meantime, the pressure data were played back into a transient recorder for quick-look analysis using Polaroid prints of the pressure-time histories. After it was safe to return inside the shock tunnel, SwRI personnel recorded the condition of each model shelter. The tested shelters were then carefully disassembled to determine their internal condition and then finally removed altogether from the test bed. The test bed was then readied for the next set of shelters to be tested.

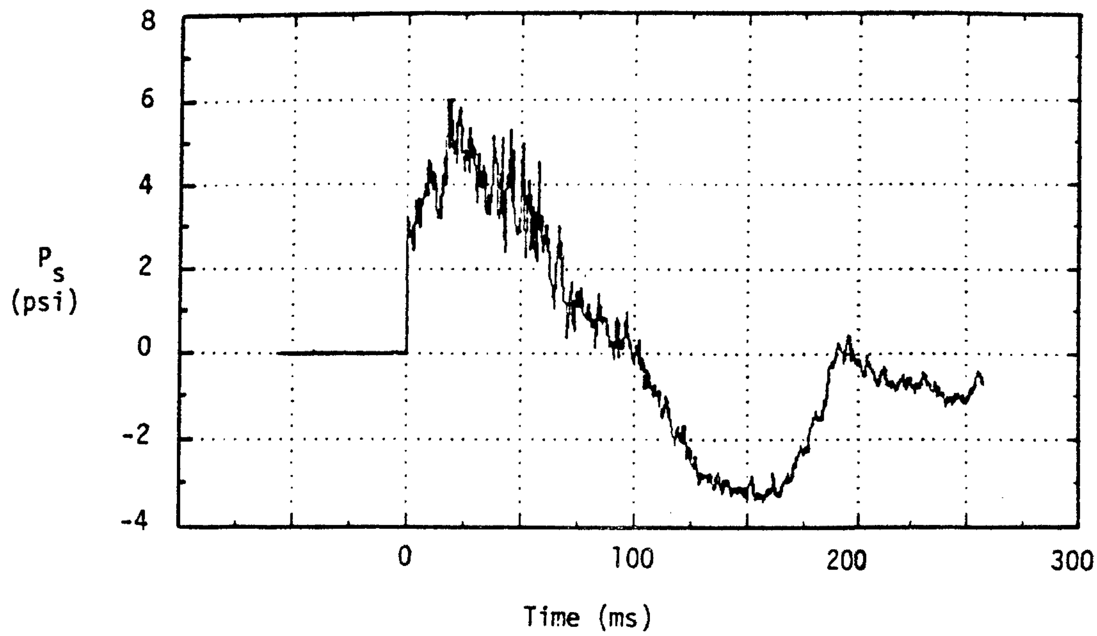
SUMMARY OF RESULTS

External Pressure Data

Up to 12 pressure measurements were made in each experiment. Five of these measurements were of external overpressures, two on one wall of the tunnel and three on the soil bed surface as shown in Figure 7. The rest of the transducers used on each test were installed on both the response models and the rigid models of the expedient shelters to measure the internal pressure leakage. Three different overpressure levels were used on the 12 tests. These were achieved by varying the number of Primacord® strands detonated in the compression tube of the shock tunnel. To achieve the lowest pressure level, two strands were used. The intermediate pressure load was achieved using four strands. For the highest pressure level, six strands were used. Analysis of the data traces for all three overpressure levels indicated a similar loading function in all cases. The five pressure transducers used for external measurements were P1 and P2 located on the soil surface at the front of the test bed, P10 located on the wall at the front of the test section, P9 located on soil surface at the rear of the test bed, and P11 located on the wall at the rear of the test section. Figure 17 shows two examples of the data recorded by P1 for an intermediate and a high overpressure test. These measurements made on the surface of the test bed just upstream of the first row of test shelters show oscillating high-frequency pressure pulses superimposed on the much lower frequency, larger amplitude pressure traces. These types of pressure records are quite similar to those recorded previously by various investigators using the Fort Cronkhite shock tunnel, and are representative of those made on each of the twelve tests at the five external locations on the various surfaces of the test section of the tunnel.

The peak overpressure for each of the five surface pressure transducers was obtained by a visual regression of the long duration pressure pulse through the high-frequency pressure oscillations. Table 4 summarizes the results of averaging the individual pressure measurements on each test. The corresponding estimated standard deviation for each set of measurements is also tabulated. As indicated by the deviation on this table, the measurements from each test were quite repeatable with most average overpressures having

(a) Intermediate Overpressure Test



(b) High Overpressure Test

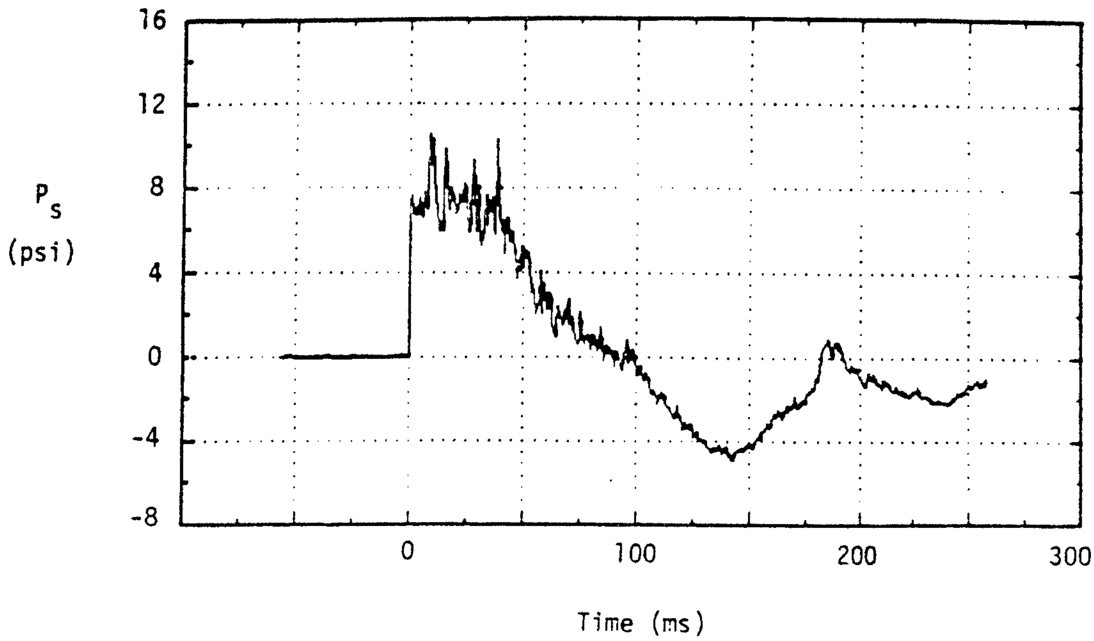


Figure 17. Test Bed Surface Overpressure Measurements

Table 4. Average Test Overpressures

Test No.	Overpressure (psi)	Deviation (±%)
01	2.96	12
02	2.82	7
03	3.03	6
04	2.84	9
05	2.54	10
06	8.64	4
07	9.20	5
08	8.82	5
09	4.54	7
10	4.72	7
11	4.52	9
12	8.53	2

deviations considerably less than ten percent. By averaging every measurement made on the low, intermediate, and high pressure tests, respectively, the three nominal test overpressures loading the model shelters were 2.8 (± 11%), 4.6 (± 7%), and 8.8 (± 5%) psig.

Internal Shelter Pressures

Measurement of the internal shelter pressures was made with transducers mounted on both the rigid and the response models. On every test, two transducers were mounted on each of the two rigid shelters, R5 and R8. In addition, up to three response models were instrumented in every test. The transducers used in the response models were rotated among the test items from test to test to obtain representative data from within each type of response model for as many pressure levels as was possible. In most cases, the peak pressure measured inside each shelter was essentially the same as measured by the external surface mounted transducers. Also, in most cases the time-histories recorded by the internal transducers was similar to that of the exterior ones with the exception that the high-frequency oscillations were filtered acoustically. In some instances the rise time of the pressure pulse is definitely slower within a shelter, and the peak pressure somewhat attenuated as compared to the external overpressure.

Figures 18 through 23 are examples of pressure-time records obtained from transducers sensing the internal pressure in each of the response and rigid models. The data traces in Figures 18 through 20 are for tests in which the surface overpressure measured was a nominal 4.6 psig. These records from shelters 2, 3, and 8, can be compared to those in Figure 17a to see how the internal geometry of each shelter affects the pressure buildup within the shelter. The data traces in Figures 21 through 23 are for a 8.8 psig nominal overpressure test. These data traces from shelters 5, 6, and 7 can be compared to those in Figure 17b to see the similarities and differences between the internal and external overpressures measured.

For example, the internal pressure in shelter 2, Figure 18, is quite similar to the external overpressures shown in Figure 17a. On the other hand, the internal pressure in shelter 3, Figure 19, shows a much slower rise time and considerably fewer high-frequency oscillations than the external overpressure records. These differences resulted primarily from the entrance to shelter 3 being mostly closed off by model sandbags as instructed in the building plans in Reference 1, while the entrances to shelter 2 are basically open. For shelter 6, the rise time in Figure 22 is somewhat slower than that in Figure 17b due to the relatively long entranceway for this shelter. An even slower rise time can be observed in Figure 23 for the pressure measured in shelter 7, which has even longer entrances leading into the shelter space.

For the two shelters, 5 and 8, for which rigid models were used to measure internal pressures, the pressure data from the rigid models were very similar in every respect to the data from the corresponding response models. The main difference observed was more reflections within the rigid models from the overstrength walls, floor, and roof as compared to the response models.

Shelter Structural Evaluation

Each of the 96 response model shelters was inspected thoroughly after being tested and an evaluation made as to the possible survival of the occupants. The criteria for survival were based primarily on whether the occupants would have been able to survive any structural or soil failures observed in the shelter after it was tested. In some cases it was obvious that unless the soil cover was replaced over the shelter after the blast loading, little or no fallout protection would have been available to the occupants. However, this was not used as part of the blast survival

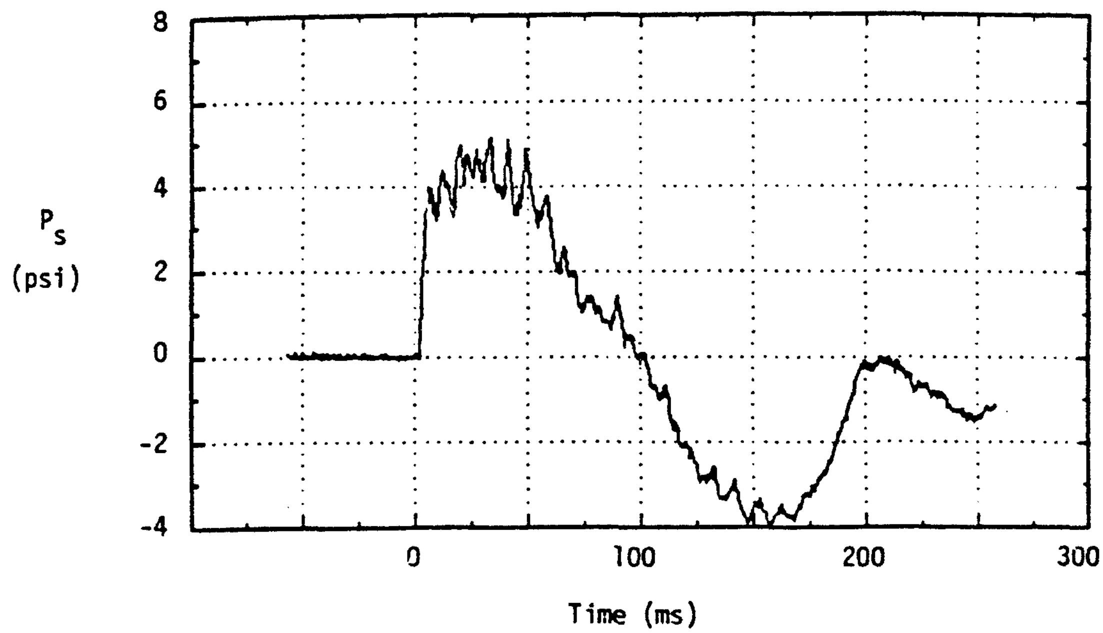


Figure 18. Internal Pressure for Door-Covered Trench Shelter

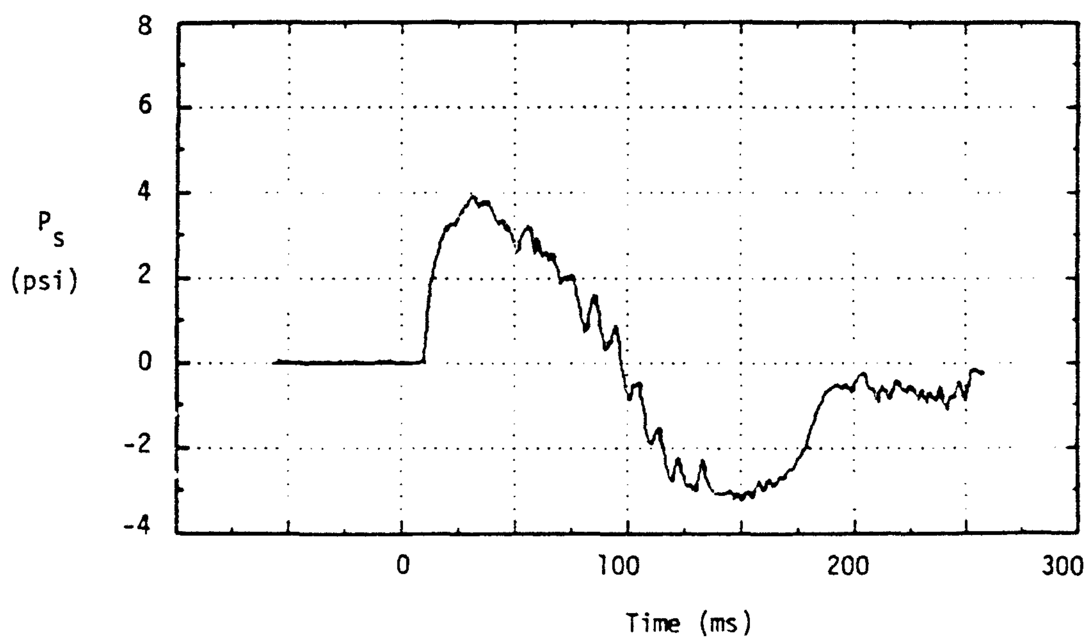


Figure 19. Internal Pressure for Above Ground Door-Covered Shelter

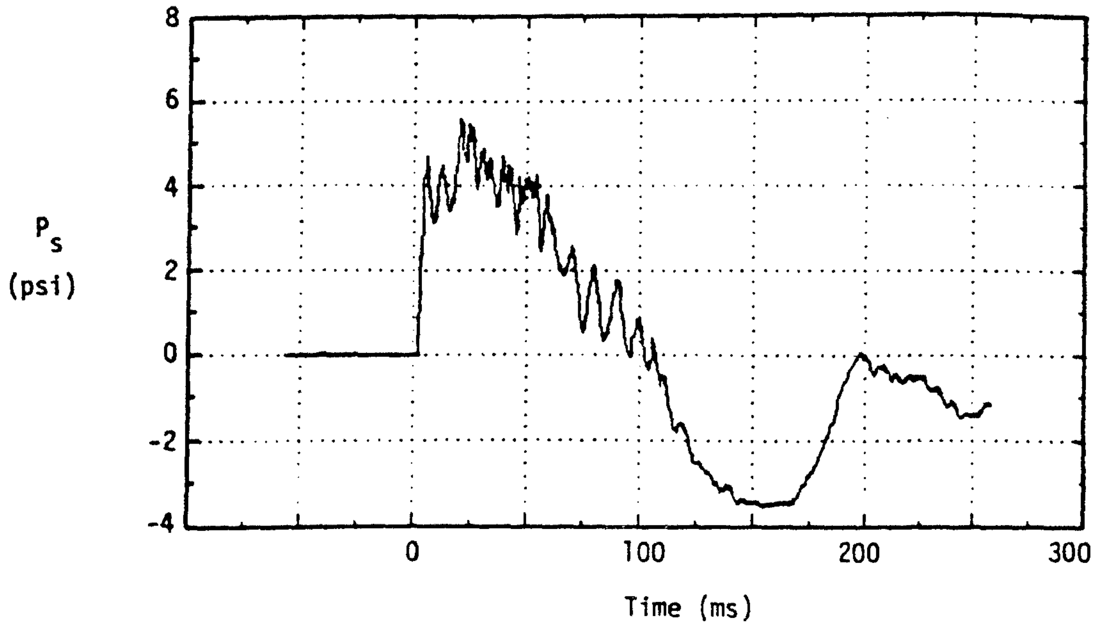


Figure 20. Internal Pressure for Log-Covered Trench Shelter

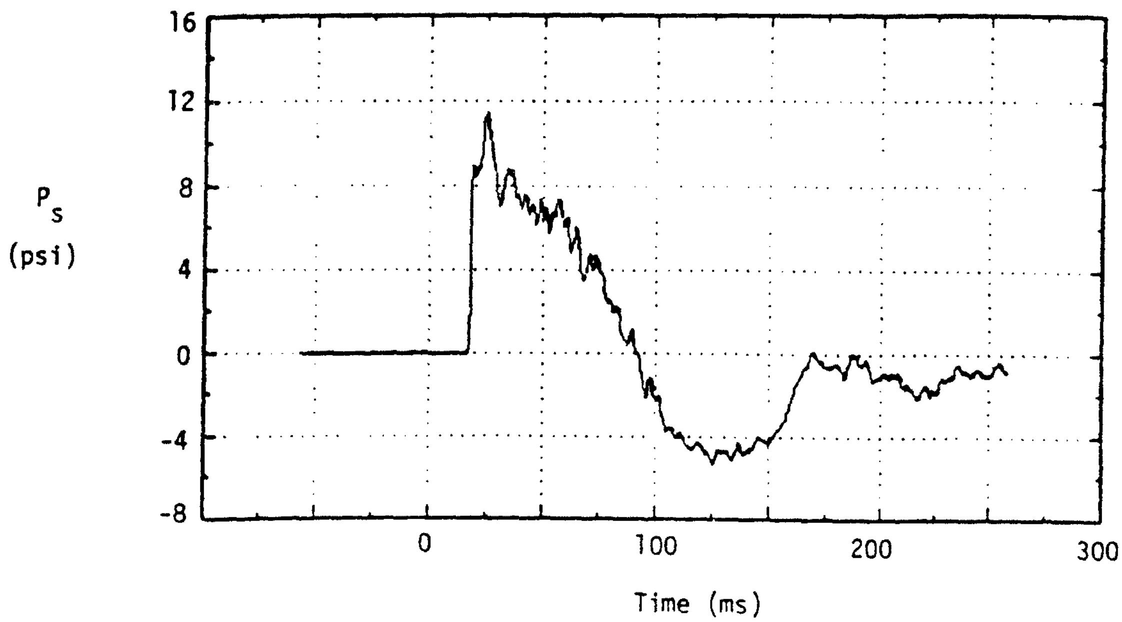


Figure 21. Internal Pressure for Crib-Walled Shelter

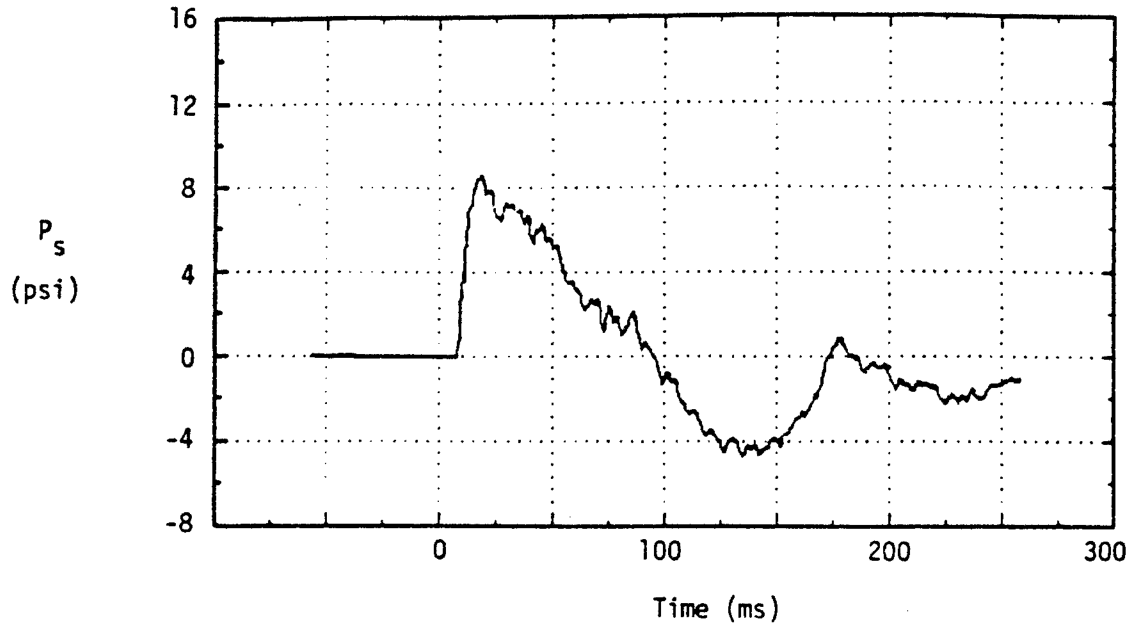


Figure 22. Internal Pressure for Ridge Pole Shelter

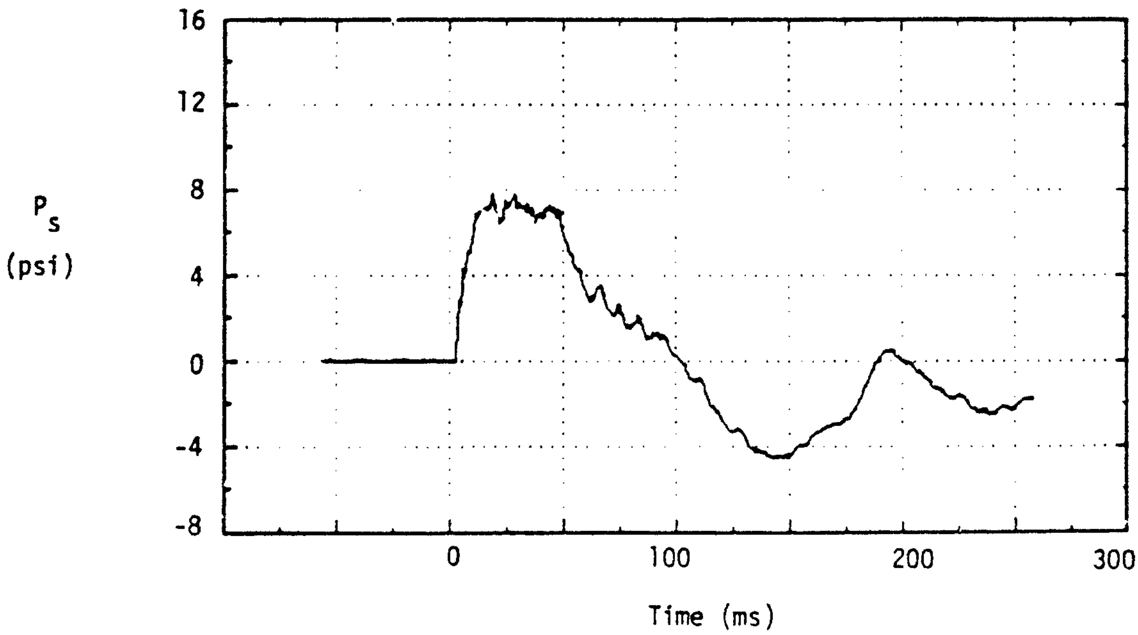


Figure 23. Internal Pressure for Small Pole Shelter

criteria. Similarly, as stated previously, the peak pressure inside most shelters during the the tests was essentially the external peak overpressure. Therefore, for some tests there probably would have been some ear damage to the shelter occupants, and to a much lesser extent, lung damage. However, up to the 8.8 psi maximum pressure tested, less than 20% of occupants would have ruptured eardrums [8, 9] and less than 1% would not have survived lung damage [10]. Therefore, structural failures listed in Table 1 were the only criteria used to determine the survivability of the shelters. Table 5 summarizes the survival assessment of the model shelters. In most cases, a yes or no rating was assigned. However, in a very few cases a marginal category also was used for shelters whose structural condition was such that the interior space appeared marginally safe for immediate survival, but perhaps not for long-term survival of its occupants.

The post-test evaluations of each shelter concentrated on the condition of the internal space of the shelter. Generally, a shelter was judged as not providing the occupants sufficient protection for survival if there was significant trench collapse, roof collapse, or rigid body translation. For example, failures for shelter 2 even at the low overpressures occurred from collapse of the door-covered, soil trench walls. For some of these model shelters, the exterior conditions after the test did not indicate major

Table 5. Model Shelter Blast Survival Evaluation

	2.8 psi Overpressure			4.6 psi Overpressure			8.8 psi Overpressure		
Shelter	Yes	Marginal	No	Yes	Marginal	No	Yes	Marginal	No
2	3	0	4	0	2*	3	1*	1*	3
3	16	0	0	1	1	5	0	0	5
5	2	0	0	1	0	3	0	1+	4++
6	5	0	0	4	0	0	5	1	0
7	2	0	0	-	-	-	5	0	0
8	1	1	6	0	0	4	0	0	6

* Doors added to shore trench sidewalls.
\+ Roof poles attached to crib walls and additional soil around cribs.
++ Roof poles attached to crib walls on one test.

damage to the shelter. However, upon internal inspection, it was obvious that the shelter had not survived the simulated nuclear blast loading. The top picture in Figure 24 shows a plan view of shelter 2 after a low pressure test. The bottom photo shows the failed trench walls. Figure 25 is an example of a door-covered trench that survived the low overpressure loading. A modification tried on this shelter on the last two tests was to shore the trench walls with model doors. This simple modification does increase the survival of this shelter.

Shelter 5 is an example of a shelter that failed in some tests due to roof collapse or translation. This above ground crib-walled shelter survived very well in the low pressure tests, but did poorly at the higher pressures. Most failures of these shelters occurred due to the roof poles and soil falling into the shelter, and in some cases for the high pressure loads due to the entire shelter being translated by the blast wave. In the low pressure tests, some of the soil cover was blown away as indicated in Figure 26, but the rest of the shelter remained intact. On the other hand, in most of the intermediate pressure tests, most of the soil cover was either blown away or fell into the interior of the shelter along with many of the roof poles. Similar, though more severe, roof response was observed on the high pressure tests as indicated in Figure 27. In addition, the entire shelter was translated back about a shelter length and in some instances rotated slightly. Two modifications were tried on the last high pressure test. The roof poles of the two crib-walled shelters used in this test were glued along the edge of the cribs and to each other to represent their being tied down along the perimeter of the shelter. One of these shelters also was covered with additional soil around the cribs and the roof so that the entryway was the only part of the wooden framework that was visible from outside. In both cases most of the soil cover was blown away, but the roof poles remained in place as shown in Figure 28. However, significant shelter translation was observed. It is very probable that with the attached roof poles modification this shelter would have survived at the 4.6 psig overpressure level. Even at 8.8 psig, this shelter can probably survive if it can be anchored to avoid rigid body translations. For example, the entire shelter could be built in a shallow trench, and, with additional soil all around, would be kept from moving during blast loading.

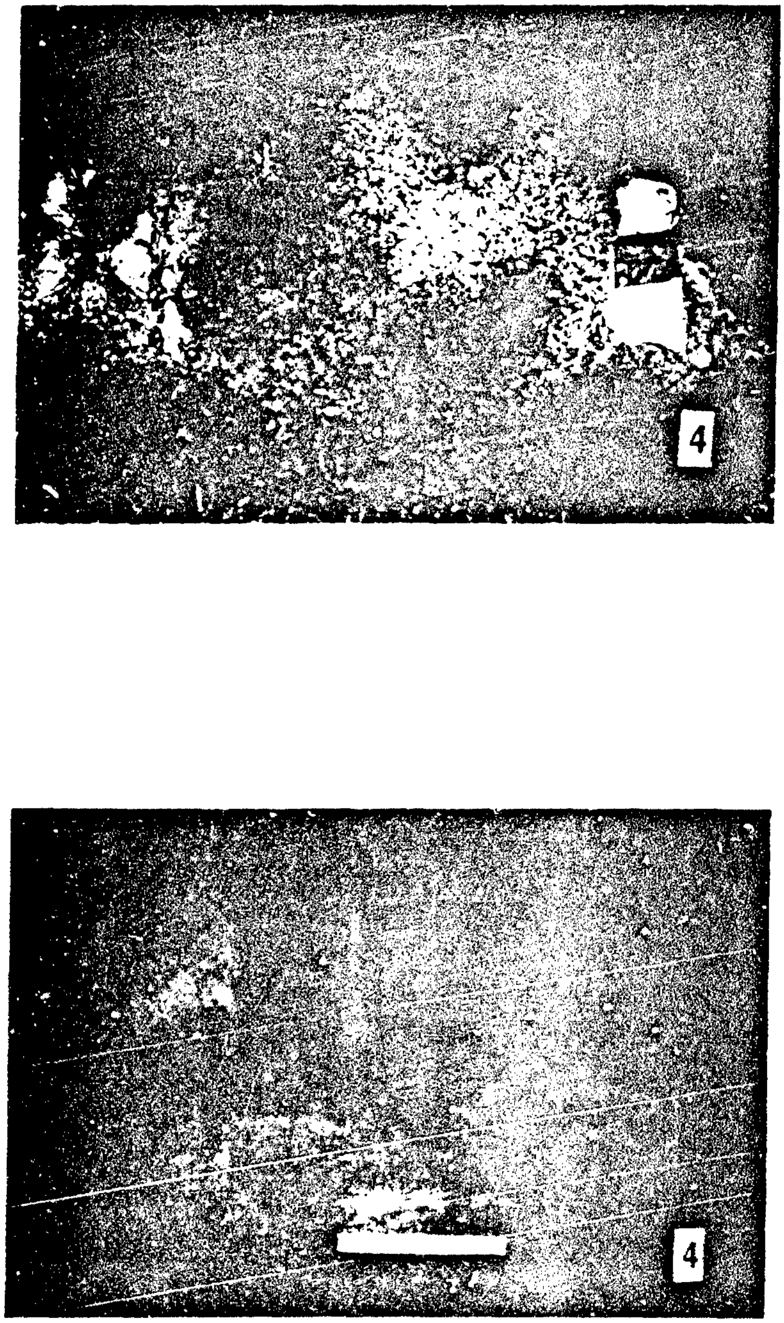
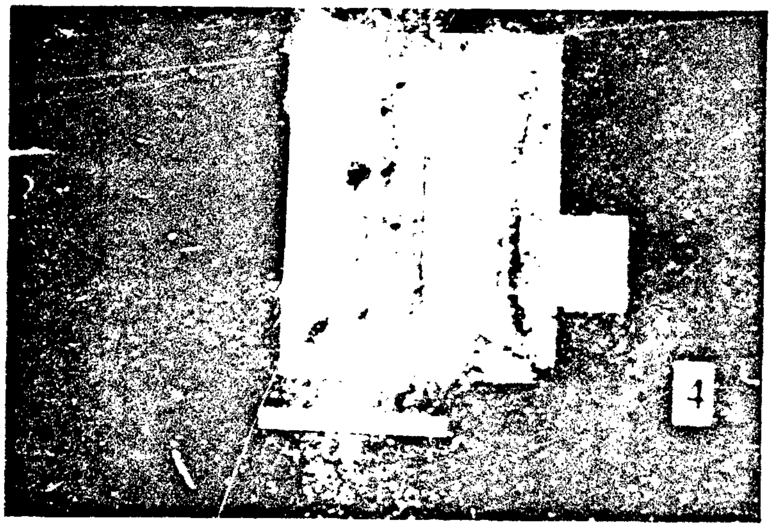


Figure 24. Non-Surviving Door-Covered Trench Shelter in Low Pressure Test



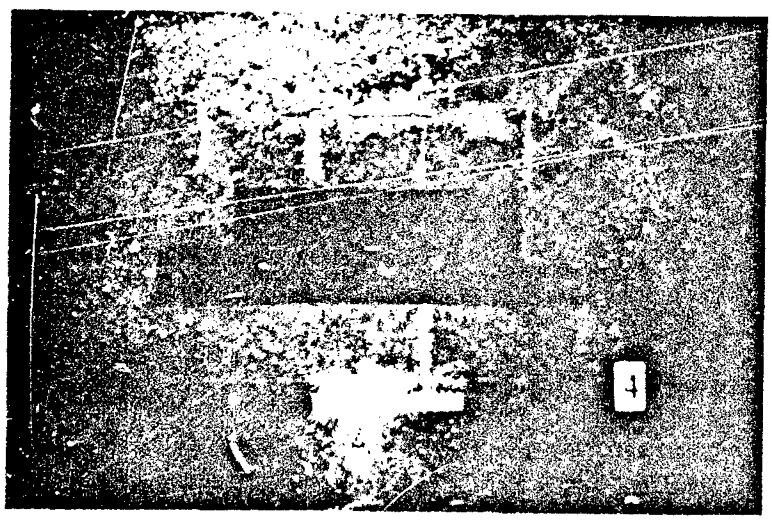


Figure 25. Surviving Door-Covered Trench Shelter in Low Pressure Test

Figure 26. Crib-Walled Shelter After Low Pressure Test

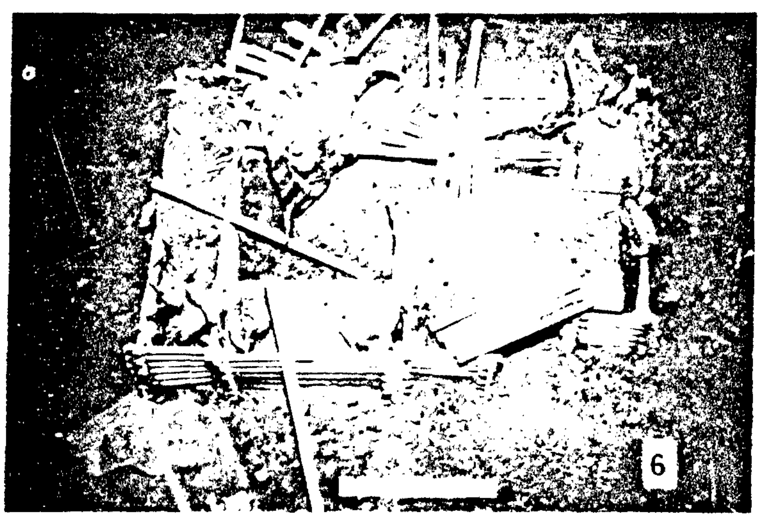


Figure 27. Crib-Walled Shelter After High Pressure Test

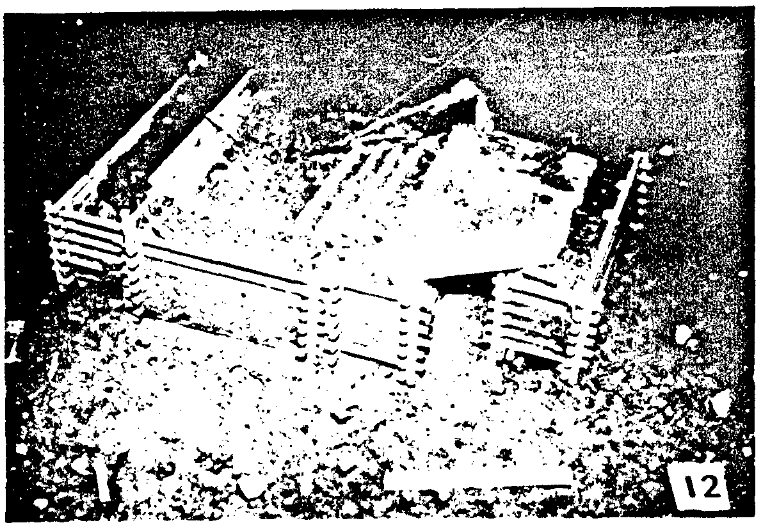


Figure 28. Modified Crib-Walled Shelter After High Pressure Test

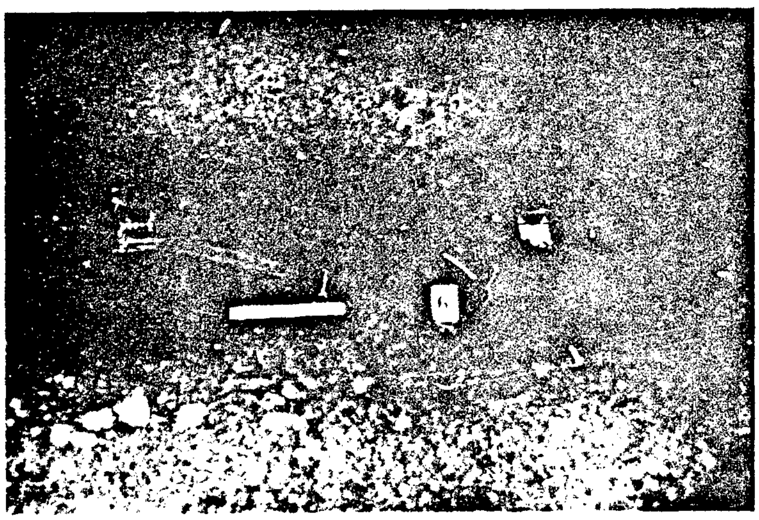


Figure 29. Small Pole Shelter After High Pressure Test

The small-pole shelter, shelter 7, provided the best blast protection in these tests. Not only did it survive structurally at the low and high overpressure loads, but it also kept most of its soil cover, even in the high pressure tests. Furthermore, as indicated earlier in the paper, the internal geometry of this shelter also provided some attenuation to the blast pressure leakage so that internal pressures were slightly lower in amplitude and had slower rise times than the external overpressures. Figure 29 shows a No. 7 shelter after a high pressure test. In these high pressure tests, some soil cover was blown away and into the entrance and vent openings. There was also some evidence of the floor soil being loosened slightly. In some case, a floor cross-frame pole was also loosened from the horizontal pole. Because this shelter always survived in the high pressure tests, it was not tested at the intermediate pressure level.

By treating the shelter survival results statistically, confidence limits can be determined for each shelter at each of the test overpressures. A binomial experiment is one in which there are only two outcomes. For the shelters, the outcome was survival or failure due to the blast loads. The estimate of the probability of survival $\bar{S}$ for each shelter can be calculated from the results in Table 5. For example, $\bar{S}$ for shelter 2 at the 2.8 psi overpressure is 3/7 or $\bar{S} = 0.43$. How much confidence can be placed on this estimate of the survival probability is a function of the number of shelters tested. The larger the number of trials, the closer that the estimated probability $\bar{S}$ will be to the actual value S. In other words $|S-\bar{S}|$ becomes smaller with an increasing number of trials.

The results presented in Table 5 were used to compute 90-percent confidence limits that each shelter provides acceptable protection at least $\bar{S}$ percent of the time when loaded by a given peak overpressure P_S. These confidence intervals on $\bar{S}$ are shown in Figure 30. Note that none of the modified shelter results was included in computing the survival probabilities, and that the marginal shelters were counted as having survived to provide the two outcomes required of a binomial experiment. The point of interest is really the lower boundary of the confidence interval. For example, the results for shelter 3 at a 2.8 overpressure load indicate a 90-percent confidence that the shelter will survive 82-percent of the time. This is based on 16 shelters tested, all of which survived. As the number of shelters

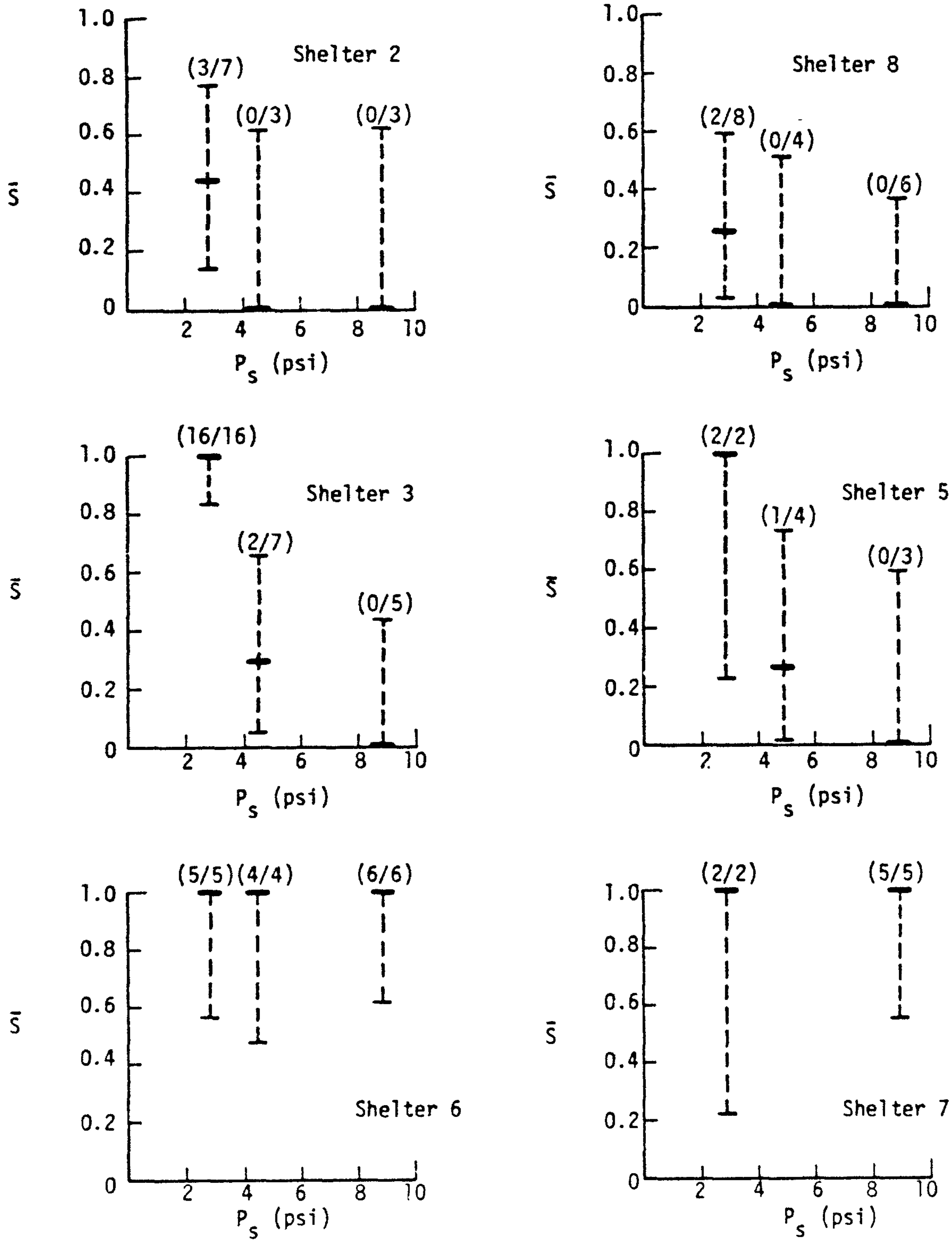


Figure 30. Confidence Intervals of 90-Percent

tested increases without a failure, the lower confidence limit at this pressure will approach 100-percent. Likewise, as shown in this figure, as the number of items tested decreases, the confidence interval will get larger. The estimated probability of survival for each shelter is denoted in Figure 30 by the bolder horizontal line at each pressure level tested. The results show very similar results for shelters 2 and 8, which performed the worst, for shelters 3 and 5, and for shelters 6 and 7, which did the best in this test program.

CLOSURE

All six expedient fallout shelters tested offer some level of blast protection. At least two model shelter of each type survived the 2.8 psig test overpressure. The log-covered trench shelter performed the worst, while the small pole shelter design proved to be best. The predominant failure mode for the shelters that did not survive was soil instability causing walls and roof to collapse. Roof collapse, in general, was another major cause of shelter failure. Translation of above-ground shelters caused some failures at the highest pressure levels. Pressures measured inside the shelters were similar to the external overpressures. Therefore, none of the wooden structural members failed since very little differential pressure developed. Results from the model tests were consistent with previous limited full-scale testing.

Some minor modifications that would improve blast survivability are recommended for the expedient shelter designs tested. Shoring the trench for all designs using trenches would significantly improve their performance particularly at the lowest and intermediate pressures tested. It is also recommended that the entrances for all shelter designs include a simple closure or other blast resistant restriction, such as sandbags, to reduce the internal pressure leakage during the blast wave passage. This would reduce eardrum damage and prevent any lung damage. Development of simple techniques for tying down shelter roof components to the walls and walls of above-ground shelters would increase their blast resistance and probability of survival even at the highest pressure tested. Because of the limitations on overpressure of the shock tunnel, it was not possible to test the small pole shelters at a pressure high enough for it not to survive. This and some of

the other designs with some of the modifications recommended should be tested in a higher pressure tunnel or high-explosive field tests. Replica modeling was successful in evaluating shelters at overpressures less than 9 psi, and should also be used in any future testing to afford testing more items and to increase the confidence of the results.

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